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LASER BALANCING SYSTEM FOR HIGH MATERIAL REMOVAL RATES

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16. Abstract

A laser technique to remove material in excess of 10 mg/s from a spinning rotor is described. This material removal rate is 20 times greater than previously reported for a surface speed of 30 m/s. Material removal enhancement was achieved by steering a focused laser beam with moving optics to increase the time of laser energy interaction with a particular location on the circumferential surface of a spinning rotor. A neodymium:yttrium aluminum garnet (Nd:YAG) pulse laser was used in this work to evaluate material removal for carbon steel, 347 stainless steel, Inconal 718, and titanium 6-4. This technique is applicable to dynamic laser balancing.

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Section 1

SUMMARY

The purpose of this report is to present the final results and the background leading up to those results as achieved in completing NASA contract NAS3-22814.

The objective and scope of this contract effort is to demonstrate, in a balancing type of operation, the use of a pulse laser that will remove material from precise locations on spinning rotors. The goal for the rate of material removal was 10 mg/s at rotor surface speeds of 30 m/s. This rate, which is necessary to make automated, in-place balancing practical and economical for normal-sized machinery, is more than an order of magnitude greater than that achieved in the past.

To achieve the goal of removing 10 mg/s from a surface moving at 30 m/s, the laser beam must move with the rotating surface in a synchronous fashion to optimize metal removal from one location on the rotating surface. A neodymium:yttrium aluminum garnet (Nd:YAG) laser operating at a maximum pulse rate of 30 pulses per second (pps) was used for this work. The length of each laser pulse was 0.63 ms and would result in a line on the rotating surface if the laser beam did not move synchronously with the moving surface.

The four materials that were investigated in this work were carbon steel, 347 stainless steel, Inconel 718, and titanium 6-4. Metal removal rates achieved at surface speeds of 30 m/s were 12.5, 18.0, 23.96, and 14.43 mg/s for carbon steel, 347 stainless steel, Inconel 718, and titanium 6-4, respectively. These data exceeded previously published data by more than an order of magnitude and in some cases exceeded the goal of the contract by a factor of two.

A survey also indicated that a pulsed YAG laser is the best for achieving this result. The YAG laser is capable of being pulsed at a much higher rate than the Nd:glass laser, which had been used in most previous work. It is difficult to exceed 6 to 7 mg with a single pulse from a laser, and one pulse per second is typically the maximum pulse rate for commercially available glass lasers. Therefore, YAG lasers appear to be the best choice.

Section 2

INTRODUCTION

Using lasers to balance rotating equipment is not new. Known applications of lasers include balancing small gyros and other similar small rotors. It has been reported that lasers have been used to balance experimental turbine spacer disks. In all laser balancing, there are some generic advantages over conventional techniques. An initial advantage is that the material can be removed while the equipment is rotating at its normal balancing speed in the balancing machine. Another advantage is the added capability of trim balancing within the equipment's normal housing without disassembly. A third advantage for laser balancing is that the balancing time can be greatly reduced for an equivalent amount of material removal. This time reduction is primarily the result of not having to stop the rotor.

Even with these advantages, this technology is limited to the amount of energy that can be delivered to a rotating surface, since the amount of material removal is a function of energy. Prior to this work, the upper limit for metal removal under static conditions over a time interval of 1 s did not exceed 6 mg, and dropped off to less than 0.8 mg when the surface was moving at 30 m/s. In the case of a moving surface, the laser beam was stationary relative to a fixed coordinate system while the work surface moved by it. Improvements have been made in the process by matching the movement of a laser beam with that of surface motion. Such synchronization caused the laser beam to appear approximately stationary to some location on a moving surface. Synchronization resulted in enhanced metal removal at surface speeds of 30 m/s. The work presented herein addresses such a metal removal enhancement technique. This technique has not been integrated into a balancing system. There is additional work required before a moving beam system could be integrated with a balancing operation where one does not know a priori at what circumferential location material must be removed.

Much of the recent work in the area of balancing with the use of a laser for material removal has been done by Mechanical Technology, Incorporated (MTI). Some of those results were reported in a NASA Contractor Report,[1] as well as in a 1979 ASME publication.[2] In this work, MTI used a Nd:glass laser that was integrated with a balancing machine. The results achieved were excellent for a stationary laser beam. That total system was computer controlled, which enabled the laser to be fired when the target was in the appropriate position.

The scope of the present work included several objectives and requirements set forth in the contract, with greatest emphasis given to the final objective of removing 10 mg/s of material from a rotor rotating at a surface speed of 30 m/s. To reach these objectives, several goals were achieved, such as

- Completing a search for the best laser(s)
- Designing a balancing rig
- Designing a moving optics system
- Fabricating and integrating the balancing rig and moving optics system
- Investigating material removal under static and dynamic conditions

A laboratory balancing test rig was designed to evaluate the parameters of a balancing type operation, as well as to determine the performance of the laser and the moving optics in removing material from the balancing test specimens. The following aspects were evaluated:

1. Static material removal rate
2. Effect of pulse time and pulse rate on material removal rate
3. Laser pulse duration as affected by system controls
4. Effect of surface speed on material removal rate and burn zone size
5. Material removal rate as a function of input energy
6. Material removal rate, on a moving target, as a function of the number of laser shots without refocusing

Parameters 1, 2, 3, and 5 were evaluated under static conditions (test specimen not moving). Parameters 2 through 6 were evaluated under dynamic conditions, over a range of balancing test specimen surface speeds, including the target specification of 30 m/s. The basic tasks that addressed the static and dynamic material removal parameters and conditions are shown in the flow diagram in Figure 1.

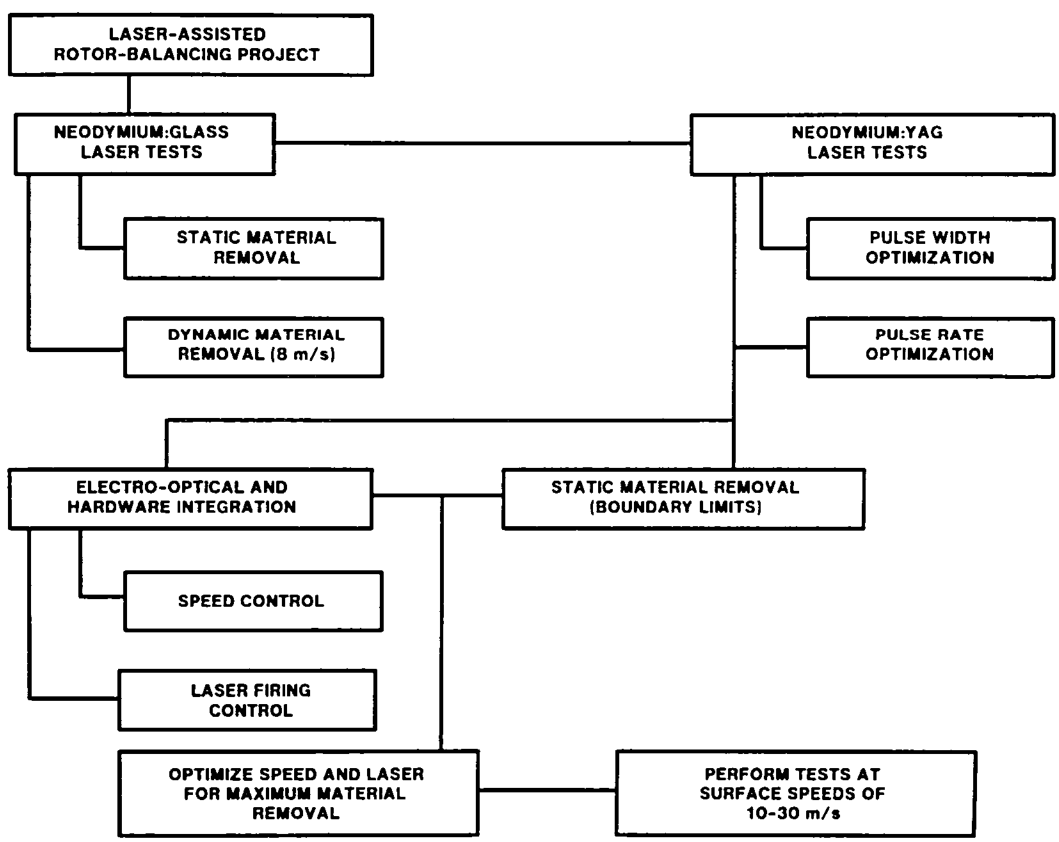

Figure 1. Flow diagram of tasks and milestones for the laser rotor balancing project

Section 3

LASER SELECTION

The laser in a balancing system must be carefully chosen on the basis of such factors as the coupling of its energy into the rotor material, the compatibility of its operating characteristics with the required target removal rate, and rotor surface speed. Thus, the important laser parameters are wavelength, output energy, beam quality, pulse width (length), and pulse rate.

Most steel, titanium, and nickel-based alloys, commonly used in turbine engine rotors, have good absorptivities to laser energy in the 0.5 to 1.2 μm wavelength range. Thus, ruby, alexandrite, and neodymium lasers with wavelengths of 0.69, 0.7 to 0.815, and 1.06 μm, respectively, merit consideration for laser rotor balancing.

To remove material from a target with a laser, the material must be heated sufficiently to be vaporized or ablated. The material removal rate is a function of the amount of laser energy absorbed. Under static conditions, the energy density on the surface is determined by the laser output energy per pulse and the focused beam spot size on the surface. When the surface of the material is moving relative to the laser beam, the situation becomes more complex because the laser energy is spread over a greater surface area, thus decreasing the effective energy (typically given in joules per square centimeter [J/cm^2]). The limiting factors of transferring energy into a material are the absorptivity of the material, the interaction of the laser beam with the plume coming off of the material surface during the pulse, and the power limitation of the laser.

Beam quality, which is proportional to the divergence of the laser beam, is important when choosing a laser to remove material from a target. Beam quality is defined as the product of the beam diameter at the laser output and the beam divergence; beam quality is given in mm-mrad. The energy density is inversely proportional to the square of the beam divergence; hence, the lower the beam divergence, the higher the energy density.

The target material removal rate is affected by both pulse time and rate. The pulse time, often referred to as pulse length or pulse width, is the time duration for which the laser energy is on. Typically, pulse widths $\geqslant$2-3 ms are required for liquefying material for welding purposes. Pulse times of 1 ms or less are required for material removal. Peak power in watts (joules per second) will increase with decreasing pulse widths for a given amount of energy (joules). As power densities of 10^6 to 10^7 W/cm^2 or greater are reached, material removal begins.

The pulse rate of a laser is the number of pulses per unit time. Several lasers are capable of delivering pulse rates $\geqslant$1 pulse per second (pps). As the pulse rate increases, the energy per pulse decreases, indicating that the average power of the laser system can not be exceeded.

Thus, for the purpose of achieving a high rate of material removal from a rapidly spinning rotor, a laser should have the proper laser wavelength for good coupling with the material, high energy output per pulse, good beam quality (low divergence), short pulse width, and high pulse rate.

The search and selection of the best lasers for a laser rotor balancing system began with a list provided in NASA RFP3-175553 and is shown in Table 1. On the basis of the

Table 1

CANDIDATE LASERS AS GIVEN IN NASA RFP 3-175553

Output (J/pulse)	Pulses per Second	Pulse Length (ms)	Model Number	Manufacturer
Neodymium: glass lasers				
5-40	0.1 or 1	0.2-10	FQG	3
60	2	0.0005-8.5203	203	1
to 120	1-5	1-10	LIMO MLaOGL	5
1-50	0-2	0.6-1.2	11E	6
Neodymium: YAG lasers				
0.5-40	5-50	0-08-10	FQY	3
1-50	1-50	0.1-10	LIMO MLa0	5
20	100	0.1-20	LaK100 LV110	5
20	100	0.1-3	LaK200 LV230	5
40	100	0.1-3	LaK400 LV480	5
40	100	0.1-20	LaK200 LV220	5
40	100	0.1-1	LaK600 LV680	5
50	200	0.25-7	SS-500	7
60	to 5	0.2-5	YL 24	4
75	100	0.1-20	LaK400 LV470	5
120	100	0.1-20	LaK600 LV670	5

Laser Manufacturers

1. BOC, Ltd.
   7 Royal Oak Way South
   Daventry, Northants, UK

2. CILAS—Compagnie Industrielle des Lasers
   Route de Nozay
   91460 Marcoussis, France

3. JK Lasers, Ltd.
   Somers Road
   Rugby, Warwickshire, UK

4. Kristalloptik Laserbau GmbH
   Am Sulzbogen 62
   D-8080 Furstenfeldbruck, West Germany

5. Lasag AG
   Bernstrasse 11
   CH-3600 Thun, Switzerland

6. Laser, Inc.
   Picker Road
   Post Office Box 537
   Sturbridge, Massachusetts 01566

7. Raytheon Corporation
   Laser Center
   Fourth Avenue
   Burlington, Massachusetts 01803

criteria given above, additional lasers were identified that had the potential for meeting the target material removal rate of 10 mg/s at a rotor surface speed of 30 m/s. These lasers are listed in Table 2. The laser that was used for the experimental work reported herein was the Raytheon Model SS-501B-9. The Control Laser 480 and the Raytheon SS-531 are two new laser models that also could meet the target removal requirements. These lasers came on the market during the course of this work. Even greater material removal would be possible with a solid-state axial gradient laser.* Such a laser has a beam divergence that is over an order of magnitude less than the solid-state lasers that are on the market today. This means a greater power density, which results in enhanced material removal.

* An axial gradient laser is one in which the laser beam, in passing through the excited laser material, is made to travel along the thermal gradient and resultant refractive index gradient in such a manner that the integrated gradient across the laser beam diameter is zero (no wave front distortion).

Table 2
CANDIDATE ADDITIONAL LASERS

Output (J/pulse)	Pulses per Second	Pulse Length (ms)	Model Number	Manufacturer
Neodymium: YAG lasers				
90	0-100	0.65-4.0	480-16	1
50	0-300	0.6-1.8	SS-531	2
45	0-100	1.0-20.0	MS300	6
Alexandrite lasers				
20	0-100	0.6-8.0	1610	5
Ruby lasers				
50	4	0.3-3.0	PD-460	2
1-50	1-5	1-10	LIMO MLaORB	3
Neodymium-glass lasers				
200	1.0	0.3-10	GE	4
90	1.0	0.75-0.95	MIGA	7

Laser Manufactures

1. Holobeam Laser, Inc.
   11222 Astronaut Boulevard
   Orlando, Florida 32809

2. Raytheon Corporation
   Laser Center
   Fourth Avenue
   Burlington, Massachusetts 01803

3. Lasag AG
   Bernstrasse 11
   CH-3600 Thun, Switzerland

4. General Electric Company
   Corporate Research and Development
   1 River Road
   Schenectady, New York 12301

5. Allied Chemical
   Electro-Optics Products Department
   Post Office Box 4901
   Warren, New Jersey 07060

6. JK Lasers, Ltd.
   Somers Road
   Rugby, Warwickshire, UK

7. Laser, Inc.
   Picker Road
   Post Office Box 537
   Sturbridge, Massachusetts 01566

Section 4

EQUIPMENT

Lasers

Two neodymium lasers were used in the work reported herein. An Nd:glass laser was used for static material removal rate experiments. The Nd:glass laser was designed and built by General Electric. This system has the following operating parameters:

1. Maximum pulse energy: 200 J
2. Maximum pulse rate: 1 pps
3. Pulse width: 0.3-10 ms
4. Average power: 60 W
5. Beam quality: 125 mm-mrad

An Nd:YAG laser was used for static and dynamic material removal rate experiments. Since the wavelength difference is only 0.006 μm (Nd:glass, 1.054 μm; and Nd:YAG, 1.060 μm) between the two lasers, their absorption into materials is basically the same. The Nd:YAG laser was a Raytheon Model SS-501B-9. This system has the the following operating parameters:

1. Maximum pulse energy: 75 J
2. Maximum pulse rate: 400 pps
3. Pulse width: 0.125-9 ms
4. Average power: 400 W
5. Beam quality: 80-100 mm-mrad

It should be noted that when either of these lasers is first pulsed, the pulse width will not be the appropriate length nor will the pulse energy be at the appropriate level. This property results from the fact that these laser systems (basically rod-type systems) are not in thermal equilibrium, which is true for all rod solid-state lasers. The glass and ruby laser require the greatest time to reach equilibrium temperature, whereas the YAG laser needs the least time. Typically, two to five pulses are required to reach equilibrium, after which pulse widths and energy outputs are very repeatable.

Balancing Rig

A mechanical system was designed and fabricated that constituted the simulation of a balancing rig. The hardware is capable of rotating a target at surface speeds in excess of 30 m/s. This was accomplished by driving a geared disk with a single variable-speed motor.

The other section of this mechanical system is the rotating optics assembly. This optics assembly is driven off the same gearing system as the target-carrying disk. There are minimal synchronization problems since the steering optics and target disk are being driven with the same gear system.

The rotating optics assembly consisted of two prism and focusing lens assemblies that are located 180° apart. This configuration allows laser energy to pass through the prism and to be focused on a moving target during every half revolution of the optics assembly. The complete system allows the focused laser beam to travel at the same speed as the moving target, so that the surface of the target appears to be stationary to the pulse of laser energy while the pulse is striking the target. The laser energy is essentially being delivered to the same spot on the target and is thus maximizing material removal. The assembled rotating optics hardware and the target rotating disk are shown in Figures 2 and 3.

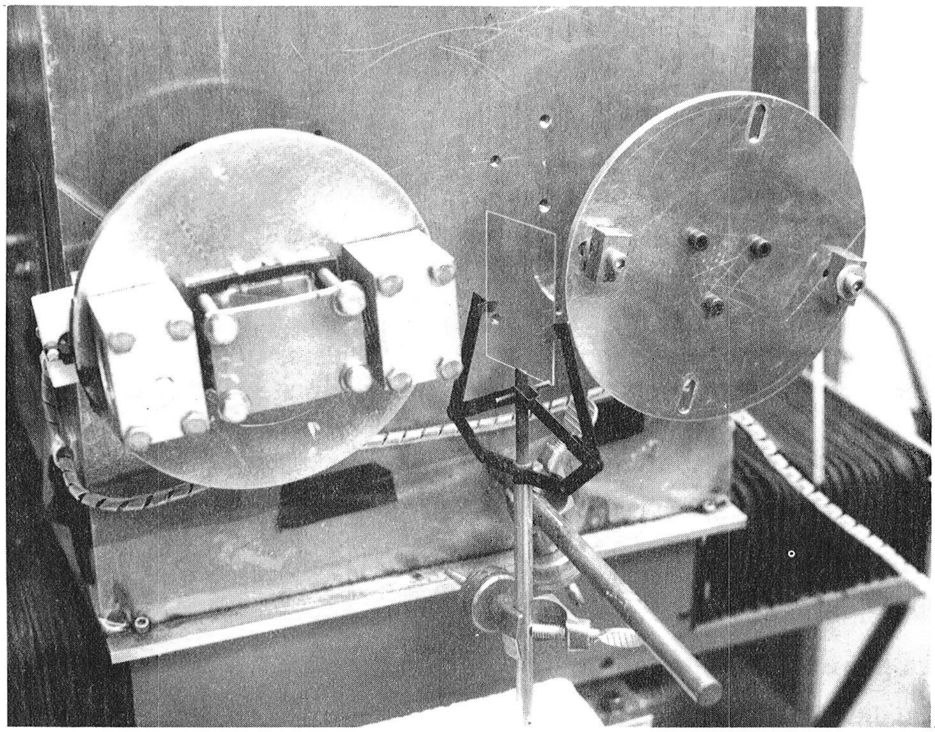

Figure 2. Rotating optics hardware and target rotating disk

Integration

The rotating optics and target system were integrated with the laser using a photon-coupled interrupter to synchronize the mechanical system with the firing of the laser. This integration system is named the optosynchronized laser interface module (OSLIM). A schematic of the synchronized integrated system is shown in Figure 4. Hardware for the integrated system is shown in Figure 5. The initiation of laser pulse energy was controlled by a signal from the photon coupler. This coupler sensed position of the optics assembly and generated a signal to fire the laser at the appropriate time. The photon coupler signal provided an accurate measure of speed and location of the target and laser trigger control. Other important features of OSLIM include filtering noise and voltage level changes from the synchronizing system, providing delay time and pulse width selection, and providing alternate delay times between revolutions to optimize material removal. In general, OSLIM provides complete control over when and where material is removed from a target moving at 30 m/s.

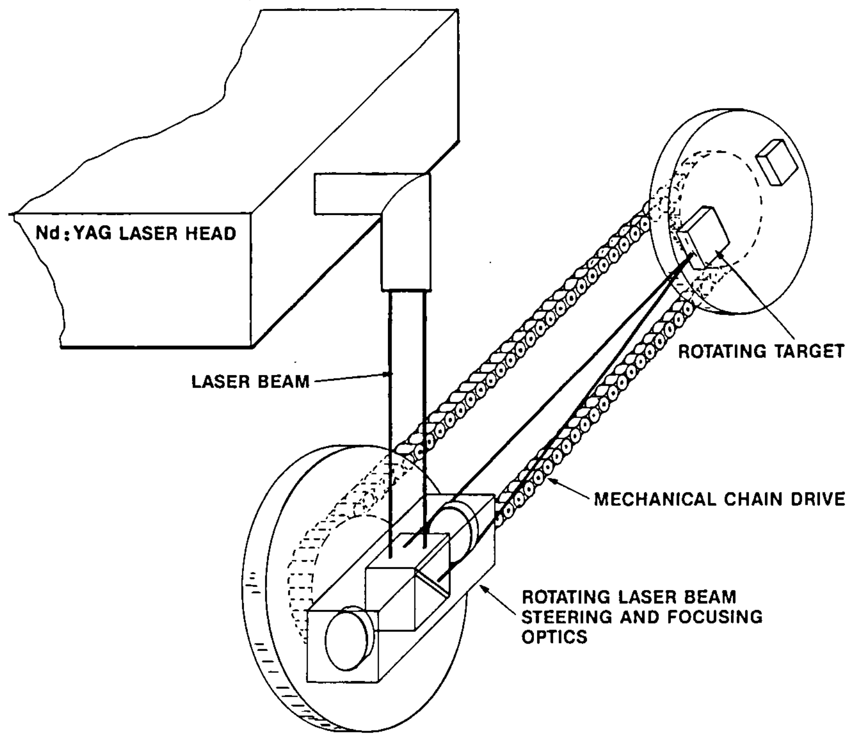

Figure 3. Schematic of laser beam rotor and target rotating disk

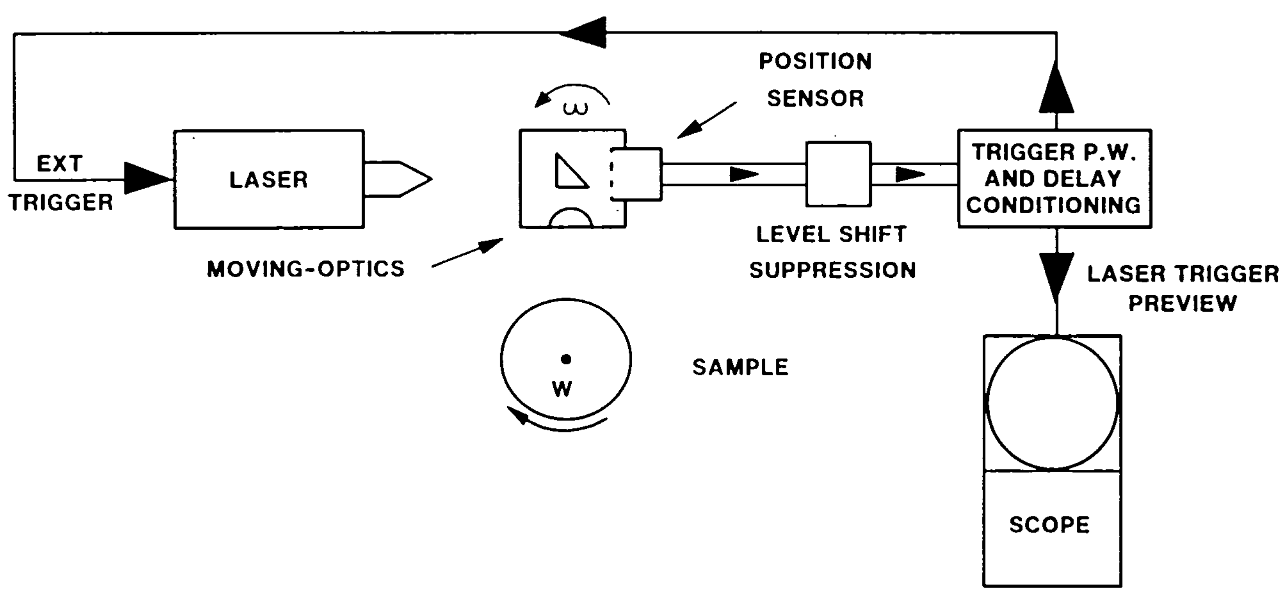

Figure 4. Schematic of laser integrated material removal system

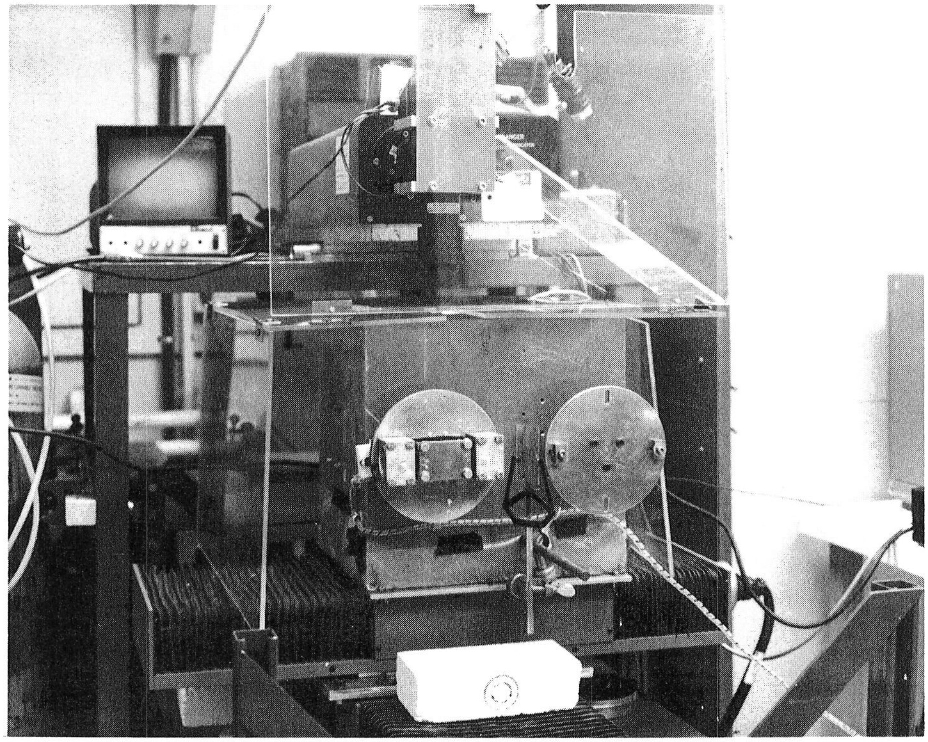

Figure 5. Laser integrated material removal system

Other equipment used in carrying out the experiments for this work included a Spectra Physics 1 mW helium:neon laser used for alignment purposes; a Tektronix four-channel storage oscilloscope used for laser triggering, pulse delay, and speed observations; and a Satorius 2400 digital analytical balance used to determine the amount of material removal.

Section 5

DISCUSSION OF EXPERIMENTAL RESULTS

All the material removal data taken in this section were obtained by following the procedural steps listed below.

1. Target samples of appropriate size and shape were fabricated.
2. Individual target samples were weighed.
3. Samples were aligned in the optimum focal position for laser interaction.
4. Laser parameters were set to correspond with optimum material removal and target sample rotational position.
5. Laser was pulsed over 1 s.
6. Samples were weighed to determine the amount of removed material.

Focusing Lens Considerations

The focal length of the objective lens in the beam delivery system of a laser will determine the resulting spot size on a work surface and therefore the energy density on that work surface. The spot size is directly proportional to the lens focal length (the shorter the focal length, the smaller the spot diameter).

With this in mind, two focal length lenses were evaluated as a function of their material-removal capability. The focal lengths of the lenses were 50 and 100 mm (2 and 4 inches). The 100-mm lens is most typically used on solid-state laser systems. As expected, a larger amount of material was removed with the 50-mm lens for all materials tested. The increase in material removal for the 50-mm lens over the 100-mm lens ranged between 70% and 90%. The relative amounts of material removal for the 50- and 100-mm lenses are shown in Figure 6. Since the 50-mm lens is difficult to protect from damage (being so close to the work- piece), most of the experiments performed for this work were done with a 100-mm lens. Hence, for all 100-mm results reported herein, there would be an improvement if a 50-mm lens were used. The 50-mm lens could be used if the protection problem is solved or the lens is considered expendable and if the lens can be physically located within 50 mm of the work surface for a real application.

Pulse Width Considerations

The pulse width (length) was optimized for maximum material removal for the lasers used in these experiments and for each of the four materials reported herein. The three pulse widths that were used during the evaluation were 0.45, 0.63, and 0.725 ms. The effect of pulse rate was also considered by varying between 10, 20, and 30 pps. For all four materials—carbon steel, 347 stainless steel, Inconel 718 and titanium 6-4—the maximum material removal occurred at 0.63 ms. This result was independent of pulse rate. An optimum pulse length will exist during laser material removal because maximum vaporization will result at maximum energy density, which is a function of pulse length. If the laser pulse is too short, the material will be shocked with minimal vaporization. Pulses that are too long will result in liquefying material which is not the optimum phase for material removal. These results, which were obtained from the Raytheon Model SS-501B-9 laser, are depicted in Figures 7 through 10. Note that the equivalent surface

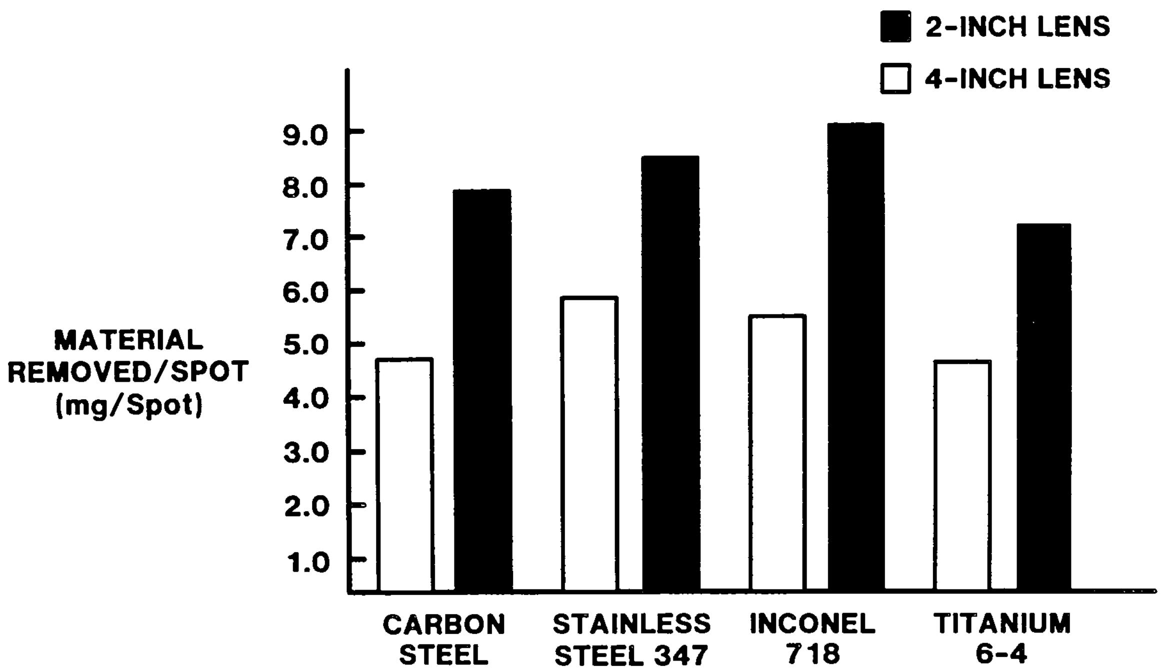

Figure 6. Material removal as a function of objective lens focal length

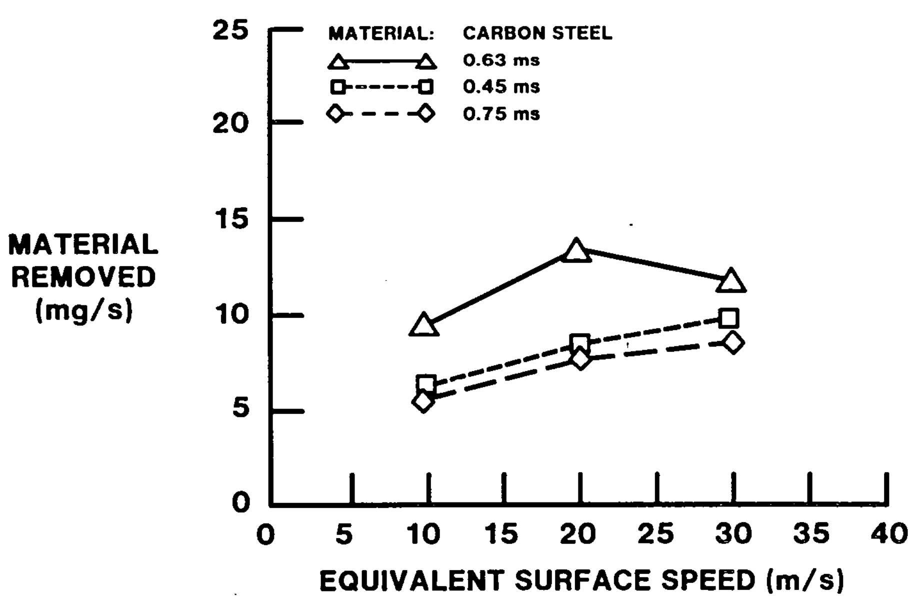

Figure 7. Material removal for various pulse widths (lengths) for carbon steel

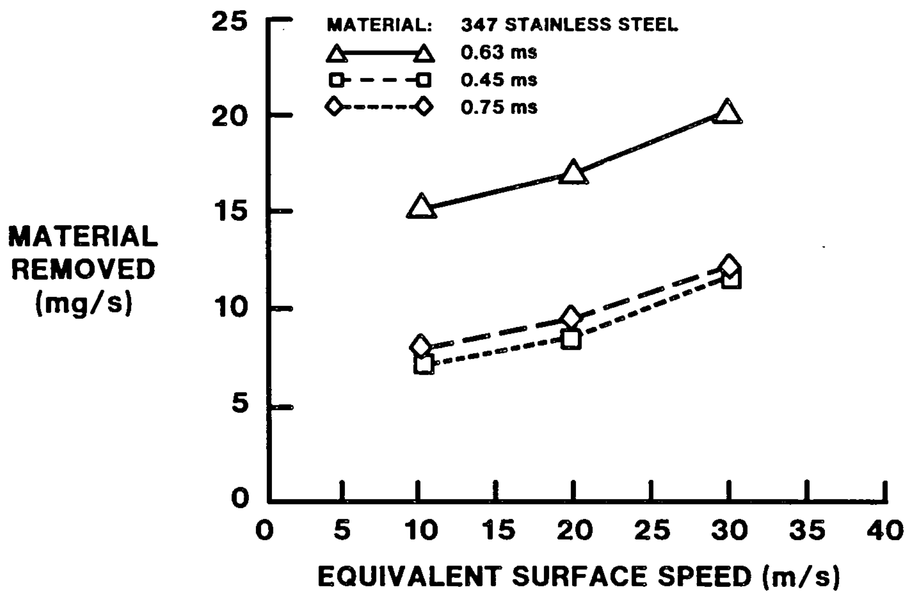

Figure 8. Material removal for various pulse widths (lengths) for 347 stainless steel

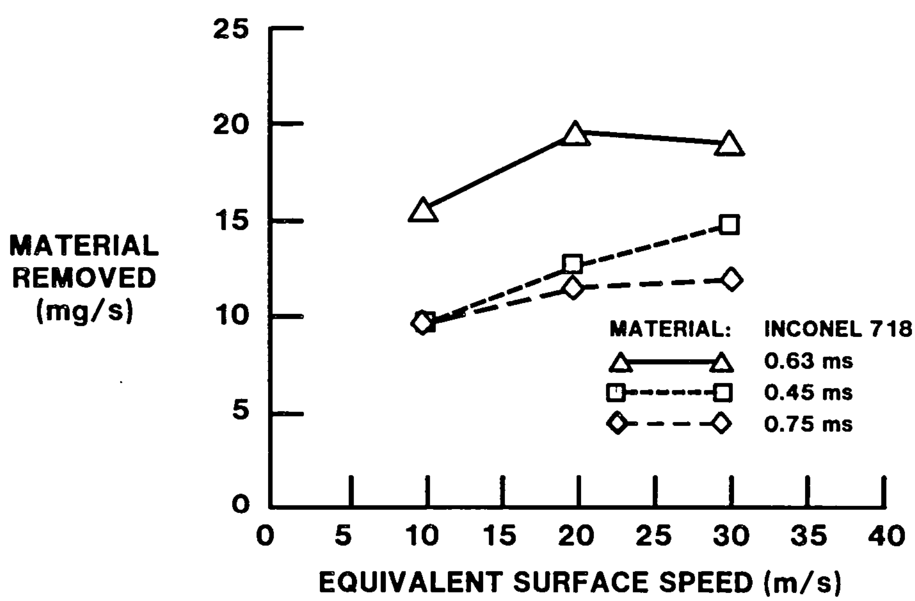

Figure 9. Material removal for various pulse widths (lengths) for Inconel 718

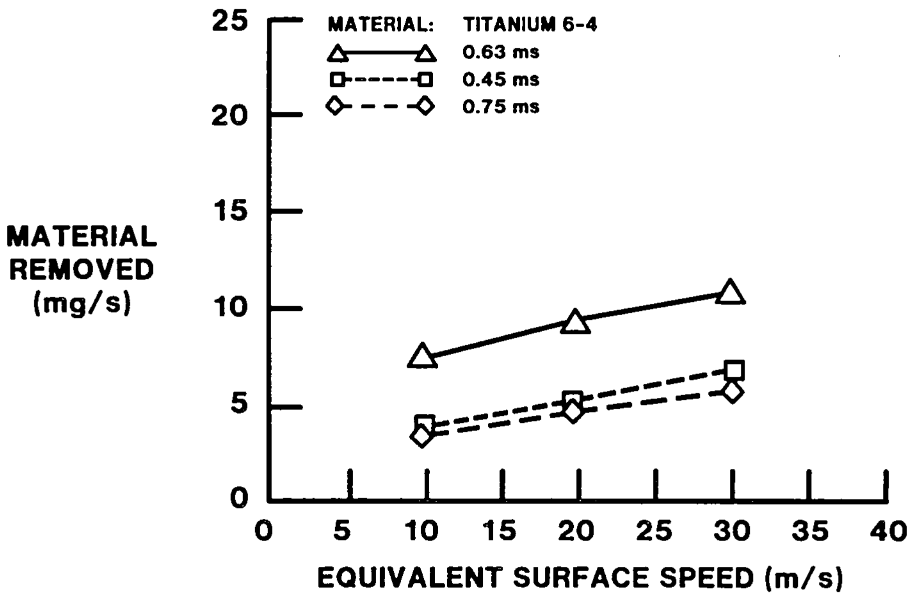

Figure 10. Material removal for various pulse widths (lengths) for titanium 6-4

speeds referred to in these figures correspond directly to the laser pulse rates of 10, 20, and 30 pps, which in turn relate directly to actual surface speeds of 10, 20, and 30 m/s.

If oxygen were used, the pulse width could have been as much as 2 ms because of momentum effect. This same momentum effect could result in improper balance sensing during a dynamic balancing operation. Momentum effect results when high-velocity oxygen gas is used to assist the removal of vaporized and liquefied material from the target material. However, the proximity of an oxygen nozzle also could be another impediment with oxygen assist. If these problems could be overcome, additional material could be removed with the same amount of laser energy but with oxygen assist.[3] The presence of oxygen allows additional material removal because more material is vaporized and liquefied from the exothermic reaction.

Stationary Beam Material Removal

In an effort to establish a baseline for the state of the art in material removal for laser balancing, initial tests were performed with an Nd:glass laser. Since most glass lasers cannot have pulse rates greater than 1 pps, this test provided the maximum material removal in 1 s for one laser pulse. These data compare well with results by DeMuth.[2] All four materials were evaluated in this experiment. Comparisons were also made for a single pulse with the target surface moving at 8 m/s. The material removal ranged from 3.5 to 5 mg for static conditions and 1 to 2.5 mg at a surface speed of 8 m/s. These results are shown in Figure 11. The symbols used in Figure 11 represent the actual data for all the materials except for the state-of-the-art data.[2] The operating parameters for the Nd:glass laser are shown in Table 3.

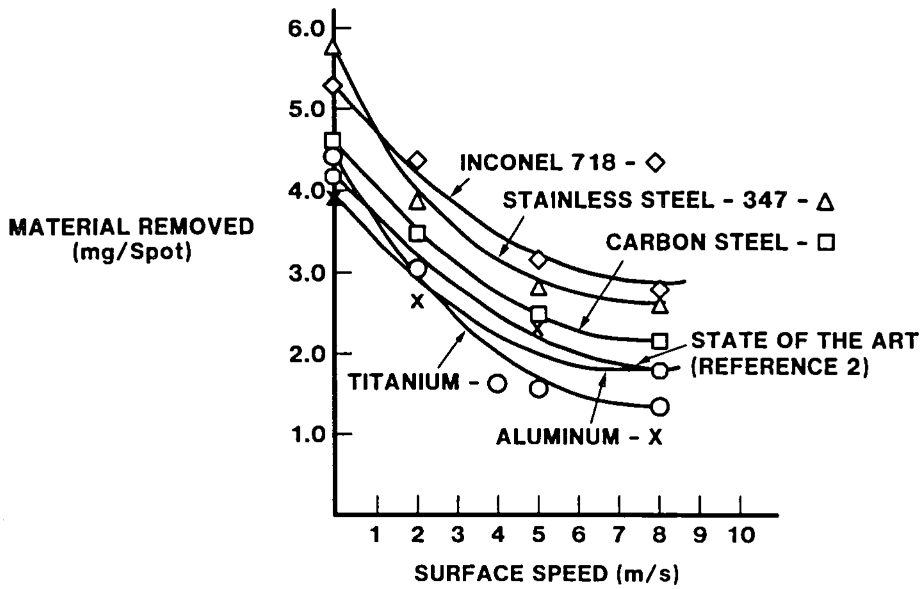

Figure 11. **A comparison of material removal with stationary optics for several alloys for Nd:glass laser. State of the art is previously reported data.**

Table 3

LASER PARAMETERS USED DURING MATERIAL REMOVAL TESTS WITH THE NEODYMIUM-GLASS PULSED LASER

Laser type	Neodymium: glass
Pulse rate	15 ppm
Pulse energy	21 J
Pulse width	0.600 ms
Optics	2- and 4-in. plano-convex lens

The second stationary beam experiment evaluated the effect of multiple pulses per second. In these tests, an Nd:YAG laser was used at pulse rates of 10, 20, and 30 pps. These variations in pulse rates correspond respectively with the surface speeds of 10, 20, and 30 m/s. The first set of tests established the maximum amount of material removal when all of the pulses were delivered to the same location on the target material. The second set of tests addressed the effect when each laser pulse was delivered to a new location (untreated material) during the 1-s time interval. The laser beam position was moved at least a distance equal to two times the laser-drilled hole diameter when interacting with a new location on the target material. These two sets of tests establish a maximum and a minimum material removal limit for 1 s under essentially stationary beam conditions. The maximum and minimum material removal boundary limits are shown as

a function of pulse rate for carbon steel, 347 stainless steel, Inconel 718, and titanium 6-4 in Figures 12 through 15, respectively. The operating parameters for the Nd:YAG laser are shown in Table 4.

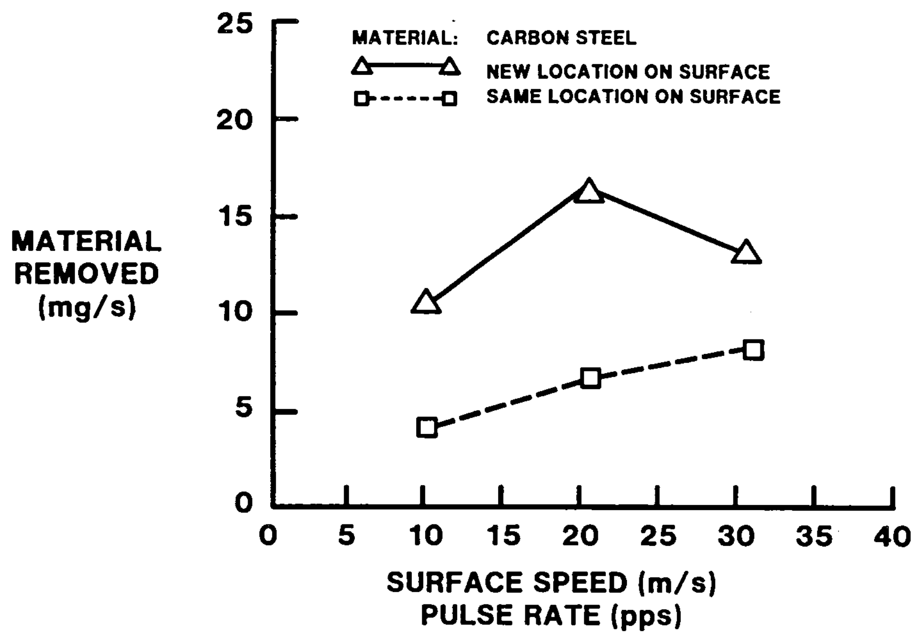

Figure 12. **Material removal boundary limits under static conditions for carbon steel**

When the maximum material removal boundary limit was established, it was found that the removal rate decreases with certain materials with increased speed or pulse rate. This result occurs because there is a decrease in the amount of energy per pulse in the laser beam when the pulse rate is increased from 20 to 30 pps. Since the amount of laser energy in each laser pulse at 30 pps is closer to the threshold for material vaporization for carbon steel, 347 stainless steel, and Inconel 718, less material is removed when interacting with a new location on a given target. This threshold for titanium 6-4 is lower; thus, this reduced material removal does not occur. When interacting with the same location on surface, this effect is minimal because all the pulses are going into the same hole, which diminishes the reflectivity effect that occurs when laser drilling untreated material with a single pulse.

Dynamic Material Removal

With all subsystem operations optimized, the task of dynamic material removal, with a moving beam, was achieved under OSLIM control. Material removal was evaluated for target surface speeds of 10, 20, and 30 m/s. The Nd:YAG laser was used for all these dynamic experiments. The optimization of the proper trigger delay and laser pulse delay relative to target speed and position was important for these tests. The laser pulse delay enabled the laser beam to impinge on two alternating locations during the 1-s material removal cycle. The two laser-treated areas were essentially tangential to each other on the target material surface. *Essentially tangential* refers to the two treated area locations being

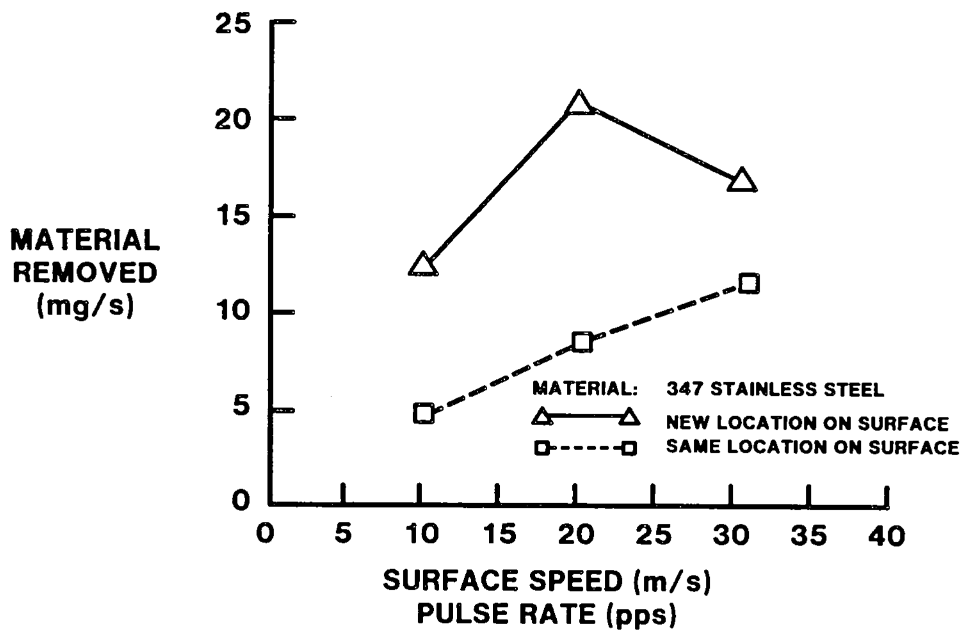

Figure 13. Material removal boundary limits under static conditions for 347 stainless steel

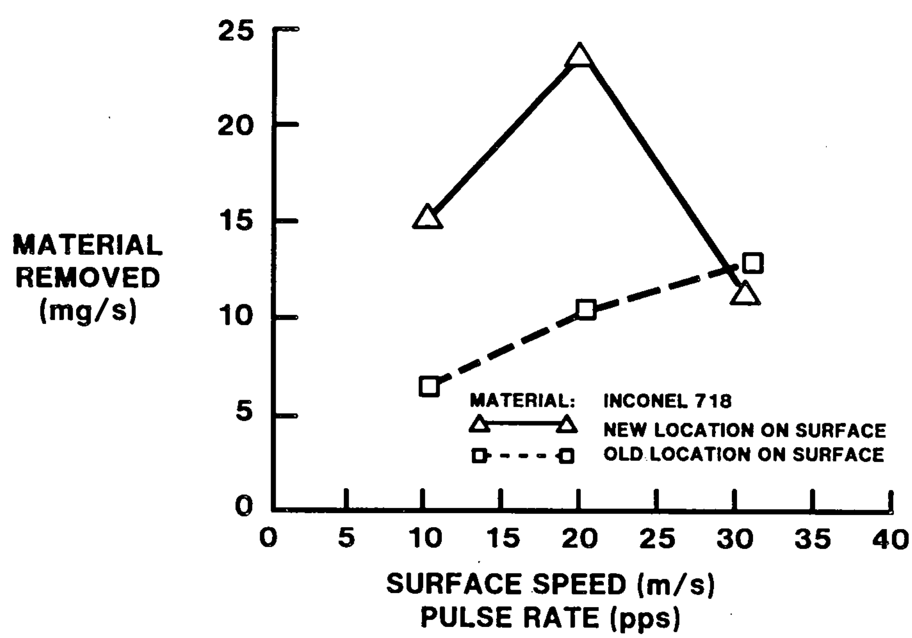

Figure 14. Material removal boundary limits under static conditions for Inconel 718

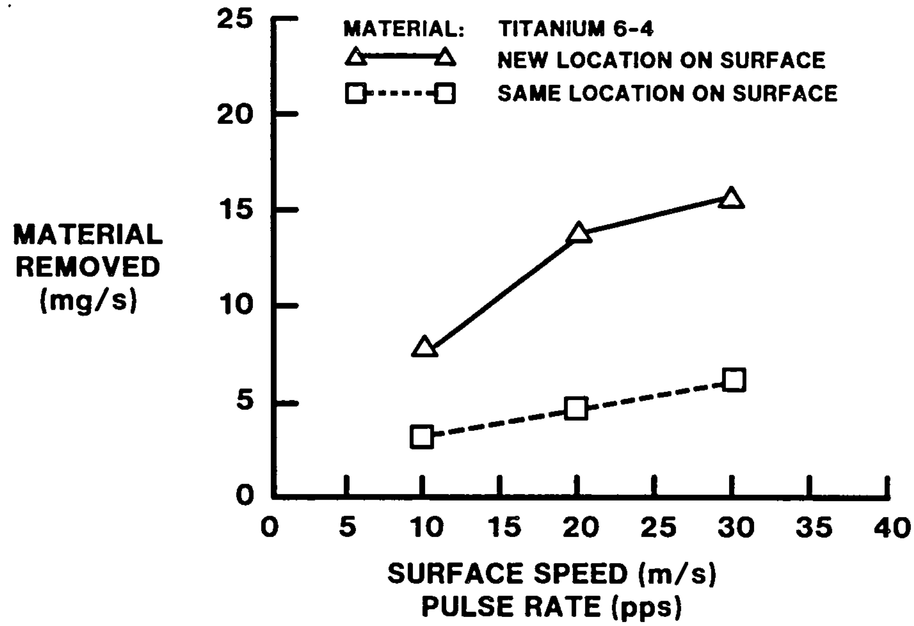

Figure 15. **Material removal boundary limits under static conditions for titanium 6-4**

Table 4

LASER PARAMETERS USED DURING MATERIAL REMOVAL TESTS WITH NEODYMIUM: YAG LASER

Speed (m/s)	10.0	20.0	30.0
Pulse width (ms)	0.63	0.63	0.63
Pulse rate (pps)	10.0	20.0	30.0
Average power (W)	50.0	100.0	180.0

close together, but with minimum overlap, to maximize material removal. With appropriate logic, additional areas could be treated in the same proximity, thus maximizing the amount of material removal. The amount of material removed for the above-mentioned surface speeds is shown in Table 5 and in Figure 16 for the four alloys of interest. For a surface speed of 30 m/s, the material removal was 12.5, 18.0, 23.96, and 14.43 mg for carbon steel, 347 stainless steel, Inconel 718, and titanium 6-4, respectively. This amount of material removal results from the use of rotating optics. When compared with stationary optics data, material removal is at least 20 times more with rotating optics for all alloys tested at surface speeds of 30 m/s. Note that the state-of-the-art data shown in Figure 16 were obtained with stationary optics; carbon steel was the material used to obtain the state-of-the-art data shown in that figure. Note also that Figure 16 shows the material removal rate, in mg/s, as a function of the number of laser shots for carbon steel, 347 stainless steel, Inconel 718, and titanium 6-4. In almost all cases, the material removal increases with increased pulse rate because of a corresponding increase in average

Table 5

LASER REMOVED MATERIAL LEVELS (mg/s)
AT ROTATIONAL SURFACE SPEEDS UP TO 30 m/s

				Symbol
Speed (m/s)	10.00	20.00	30.00	
Previous reports	Reference 2			○
Carbon steel	9.75	11.53	12.50	△
Stainless steel	12.05	13.90	18.00	□
Inconel 718	13.63	15.43	23.96	◇
Titanium 6-4	11.10	9.00	14.43	*

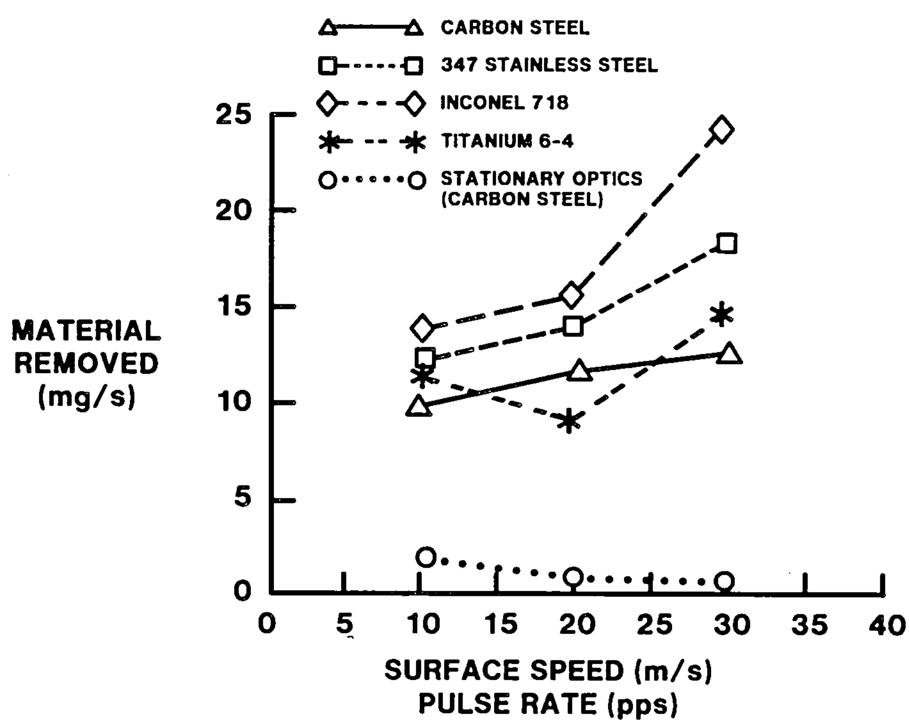

Figure 16. Rotating optics material removal data for carbon steel, 347 stainless steel, Inconel 718 and titanium 6-4 compared with stationary optics data

power input to the target, as shown in Table 4. The rotating optics material removal data are also compared with the maximum and minimum material removal limits in Figures 17 through 20. The fact that some of the tested alloys exceed the maximum material removal boundary can be attributed to a centrifugal force effect from the rotating target. Recall that the maximum (new location on target for each laser pulse) and minimum (same location on target for each laser pulse) material removal data were obtained by using stationary optics and a stationary target during the laser pulse.

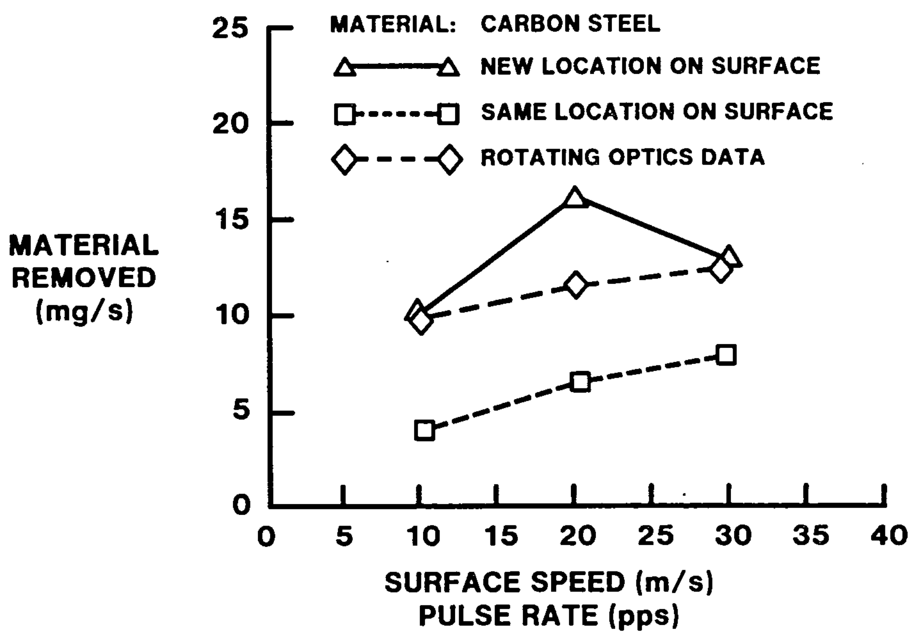

Figure 17. Comparison of rotating optics material removal data with maximum and minimum limits for carbon steel

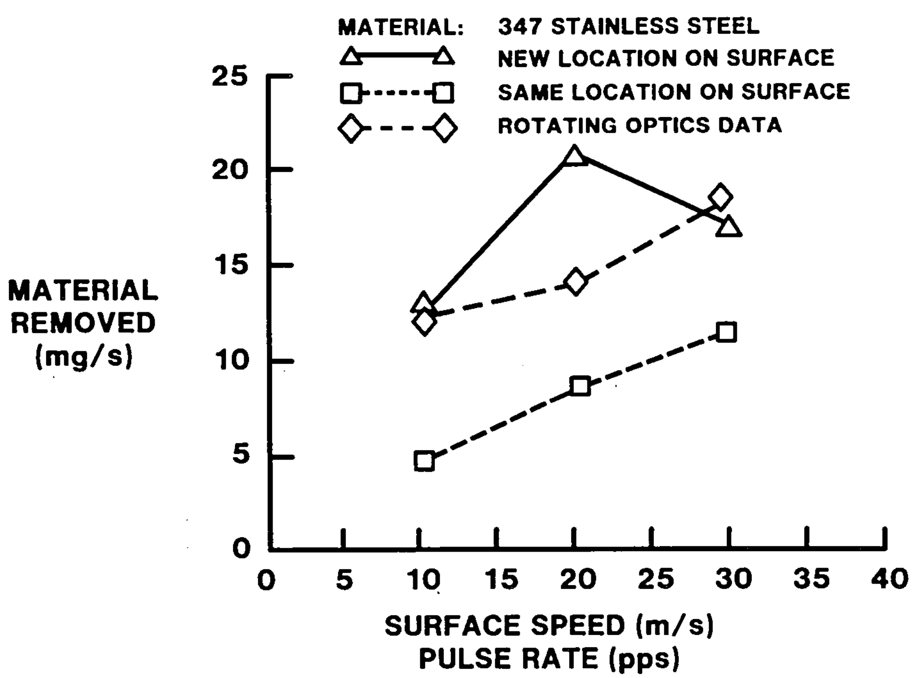

Figure 18. Comparison of rotating optics material removal data with maximum and minimum limits for 347 stainless steel

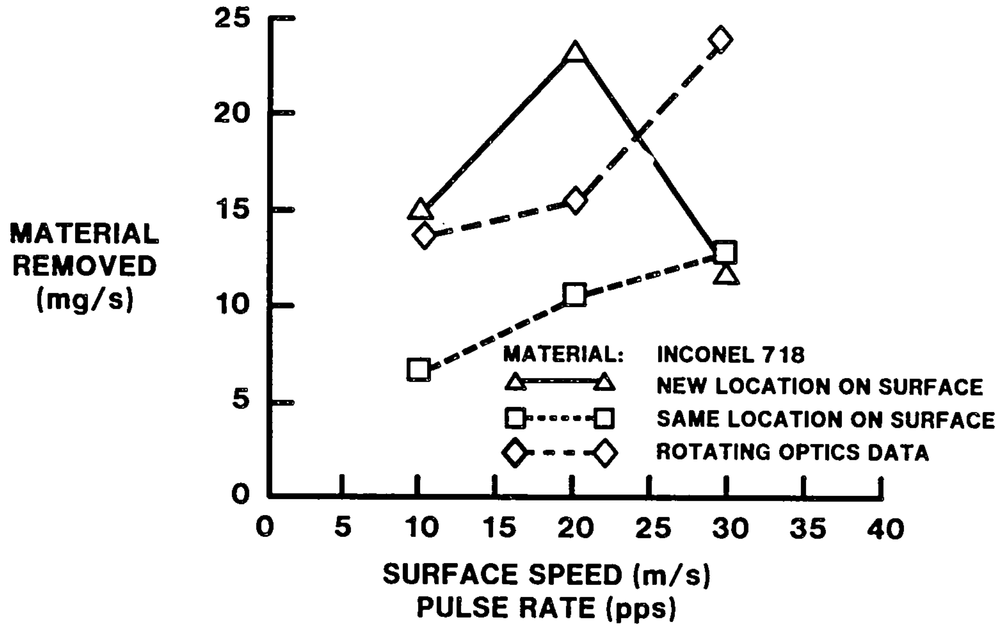

Figure 19. Comparison of rotating optics material removal data with maximum and minimum limits for Inconel 718

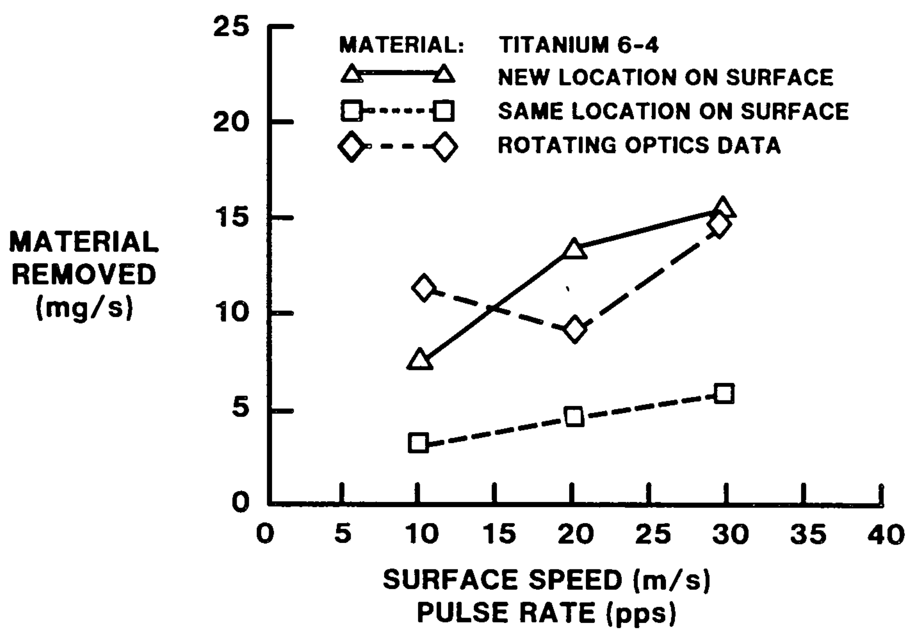

Figure 20. Comparison of rotating optics material removal data with maximum and minimum limits for titanium 6-4

Section 6

CONCLUSIONS

The work reported herein has demonstrated that the ability to remove material from the surface of a rotating target with a pulse laser can be greatly enhanced when the focused laser beam is made to appear stationary to the moving surface through the use of a rotating optics system. The goal of this work was to remove 10 mg in 1 s from a surface that was moving at 30 m/s. This goal was achieved when material in excess of 10 mg was removed for carbon steel, 347 stainless steel, Inconel 718 and titanium 6-4. Even larger amounts of material could be removed with the higher energy per pulse lasers that are now on the market, a laser with better beam quality (lower beam divergence), or with a laser that has the same amount of energy in a pulse but has a shorter wavelength than the 1.06 μm wavelength, so that more of the beam energy is absorbed by the workpiece.

Section 7

REFERENCES

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